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AND8399/D

How to Measure Bemf on the SLA-pin

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APPLICATION NOTE

Abstract

To enable the possibility to build very accurate stall and steploss algorithms as also torque adaptive applications, AMIS−305xx has a Speed and Load Angle (SLA) pin which outputs a voltage that reflects the Bemf (Back Electro Magnetic Force) voltage of the motor.

To prevent incorrect use of the SLA-pin, this application note describes how the motor driver should be operated to measure the correct Bemf voltage on the SLA-pin.

Introduction

The Bemf is sampled every so called “coil current zero crossing”. Per coil 2 zero-crossing positions exist per electrical period, resulting in a total of 4 zero crossings per electrical period. Or in short, the Bemf voltage can be measured 4 times per electrical period. Although the Bemf voltage can be measured 4 times per electrical period, it does not mean that it will be measured 4 times. The Bemf voltage will only be sampled by the motor driver if a microstep position is located on the “coil current zero crossing”. Only then a correct representation (Note 1) of the Bemf voltage can be measured on the SLA-pin. If no microstep position is located on the “coil current zero crossing”, an incorrect value will be measured on the SLA-pin.

Coil Current Zero Crossings

Next figures display 4 of the in total 7 stepping modes possible with AMIS−305xx.

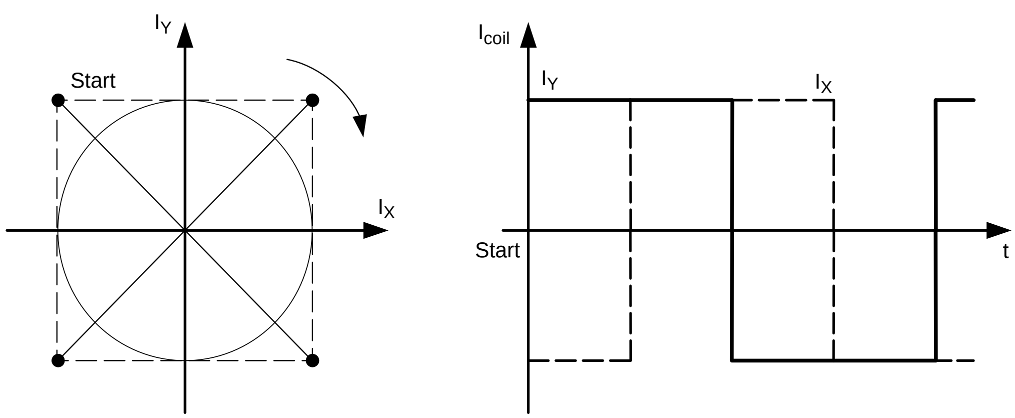

Figure 1. Full Step Mode

1. The voltage measured on the SLA-pin only represents the Bemf voltage. Depending on the SLA Gain setting [1] the SLA voltage will be equal to 1/2 or 1/4 of the real Bemf voltage.

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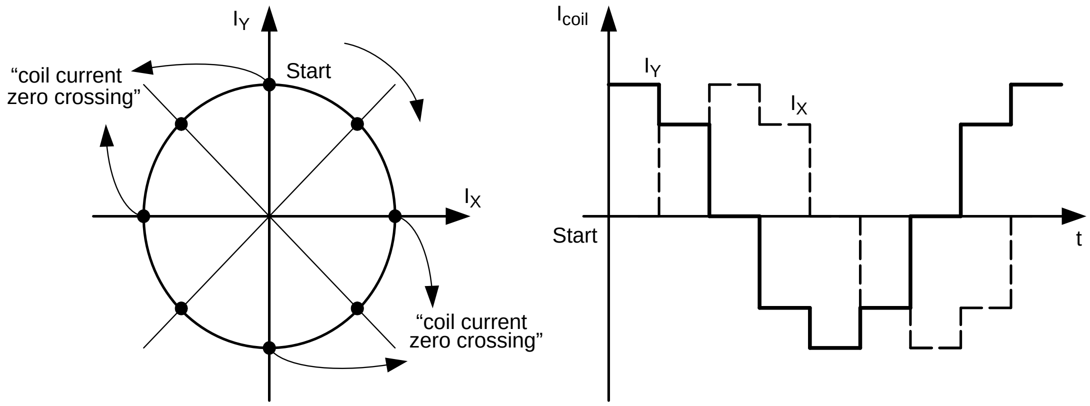

Figure 2. Half Step Compensated Mode

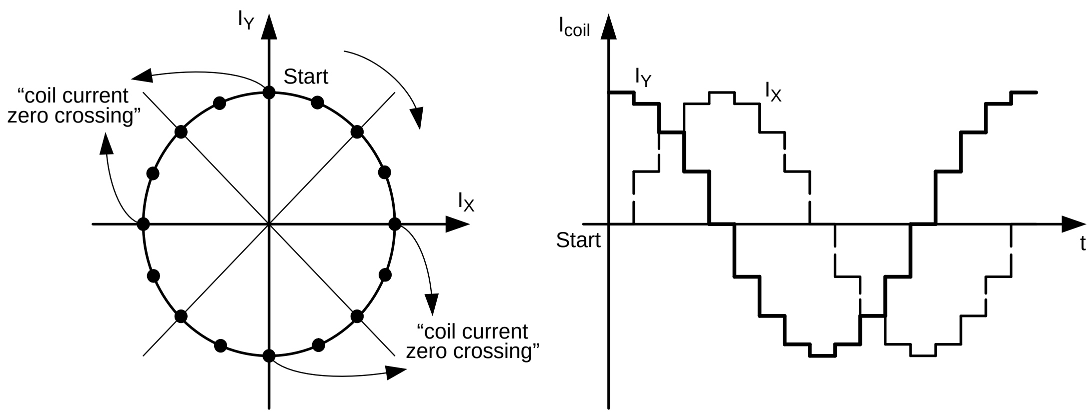

Figure 3. 1/4th Stepping Mode

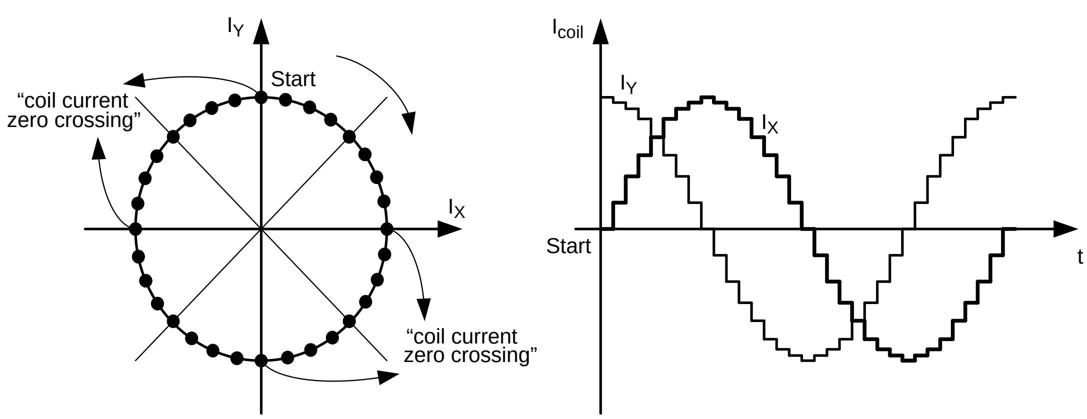

Figure 4. 1/8 Stepping Mode

As displayed in above figures, a microstep position is located on the "coil current zero crossing" except for full step mode (Note 2). Only if a microstep position is located on the "coil current zero crossing", a correct representation of the Bemf voltage can be measured on the SLA-pin.

2. See the Full Step Stepping Mode section for more info on full step stepping mode.

The several stepping modes of AMIS−305xx offers a lot of flexibility but at the same time could also cause problems when not used in a correct way. Figure 5 displays what could go wrong when switching between stepping modes is done in an incorrect way.

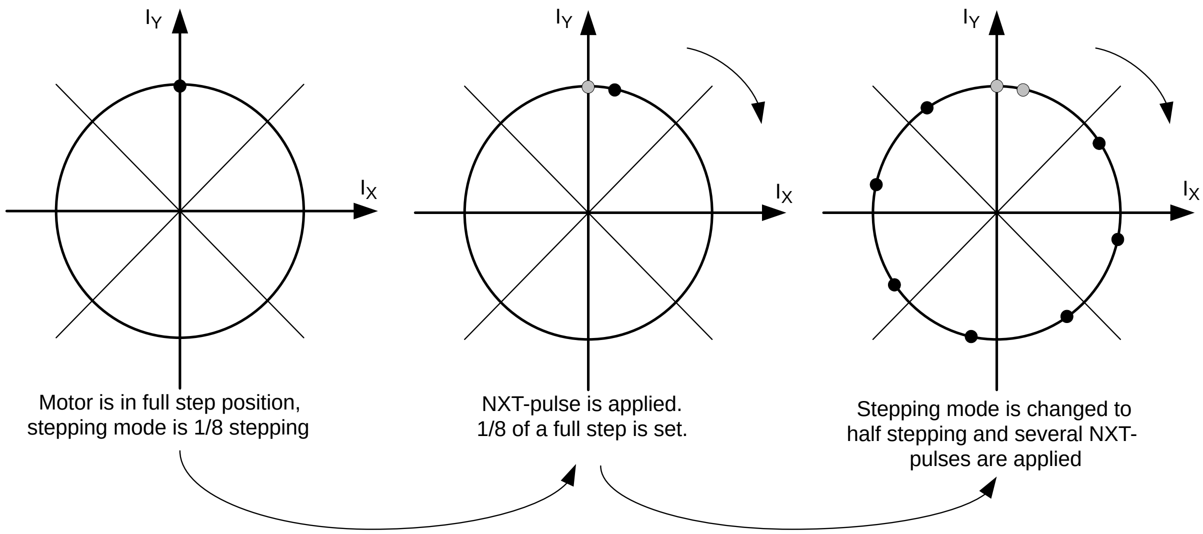

Figure 5. Changing of Stepping Mode in an Incorrect Way

Above figure demonstrates that care should be taken when changing the stepping mode to a lower resolution. When changing to a lower stepping mode, it is possible that an offset is created resulting in no microstep position at the “coil current zero crossing”. The stepper motor driver will not sample the Bemf voltage and an incorrect representation of the Bemf voltage will be measured on the SLA-pin.

Next figure displays again half stepping but now with the offset included (as displayed on the right side of Figure 5).

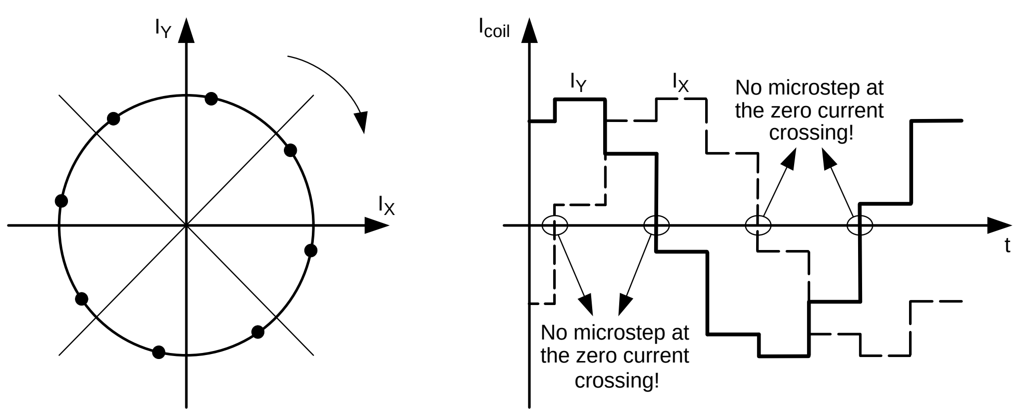

Figure 6. Half Stepping with Offset

Table 1 on page 7 can be used to know at which Microstep Position (see Status Register 3 of AMIS−305xx) the stepping mode may be changed without creating an offset. Changing to a higher resolution can be done at any moment. Changing to a lower resolution may only be done if the Microstep Position is also present in the lower stepping mode. More info on Table 1 can be found in the SLA Check section.

Below oscilloscope plots display the coil currents and the SLA voltage measured at 1/8 microstepping. In the first plot (Figure 7) no offset is created resulting in a microstep position on the "coil current zero crossing". The voltage measured on the SLA-pin will represent the real Bemf voltage of the stepper motor.

In the second plot (Figure 8) an offset is created. No microstep position is located on the "coil current zero crossing". The voltage measured on the SLA-pin will not represent the real Bemf voltage of the stepper motor.

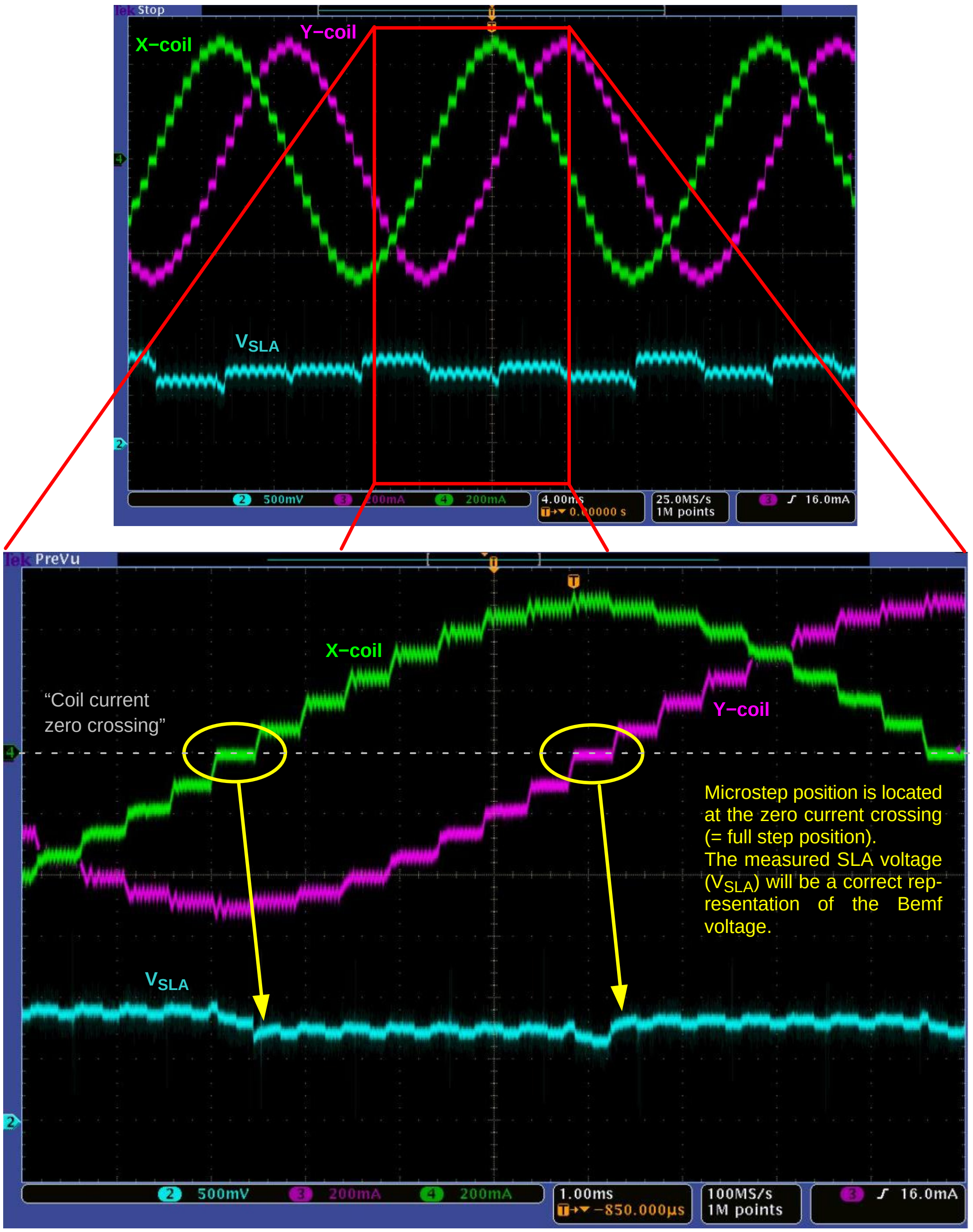

Figure 7. Oscilloscope Plot of 1/8 Microstepping with Microstep Position Located at the Zero Current Crossing

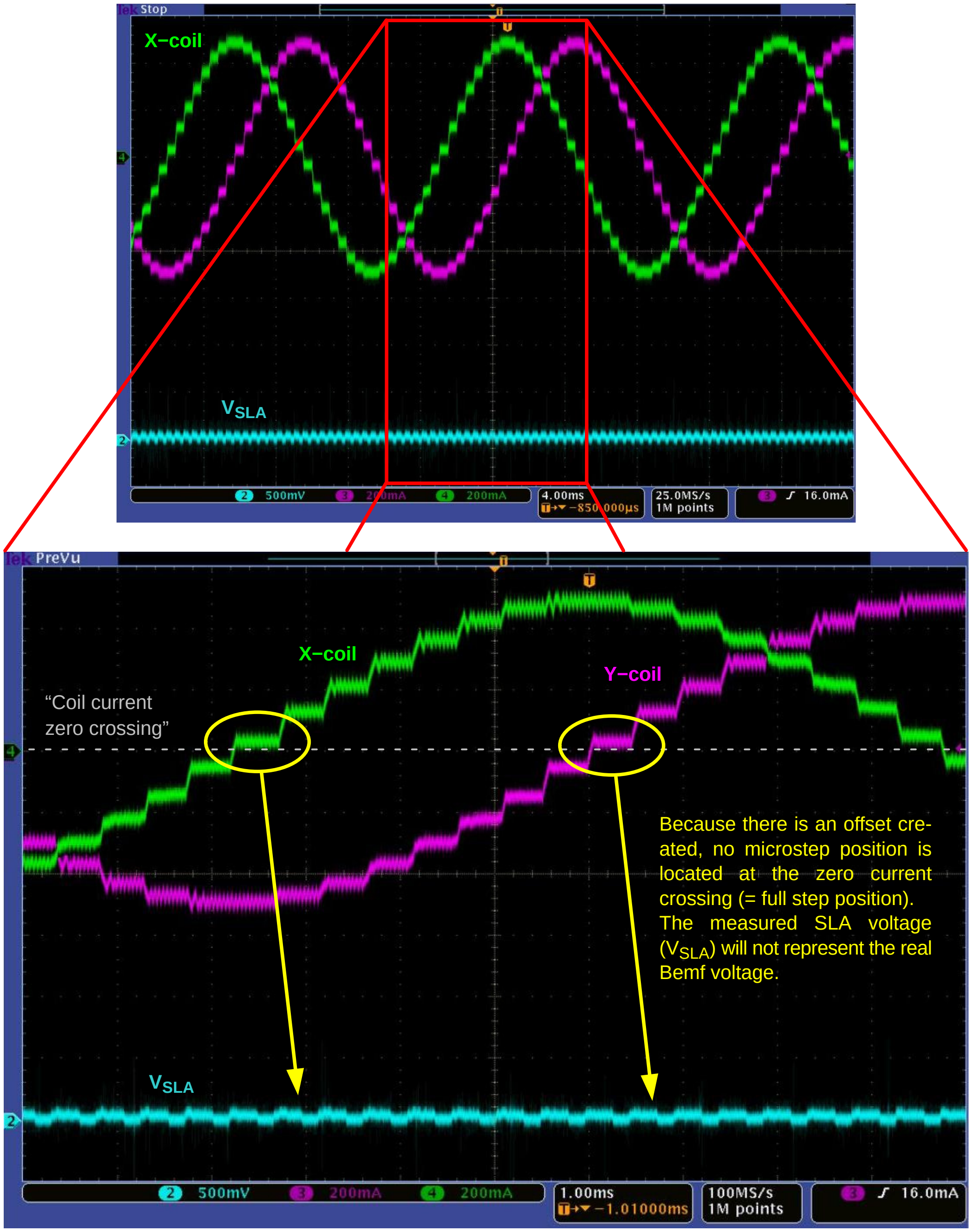

Figure 8. Oscilloscope Plot of 1/8 Microstepping with No Microstep Position Located at the Zero Current Crossing

SLA Check

Although the microcontroller controls the stepper motor driver, it’s always possible that an offset is created unwontedly. By reading out the Microstep Position (Status Register 3) the microcontroller can check if an offset is created or not.

Table 1 displays all possible Microstep Positions for all stepping modes except full step. If at any moment the read out Microstep Position is equal to a value given in this table (for a certain stepping mode), no offset is created (see also Figure 9). If another value is read out, an offset is created and no microstep position will be located on the ”coil current zero crossing” (see also Figure 10). The SLA-voltage will not represent the real Bemf of the stepper motor.

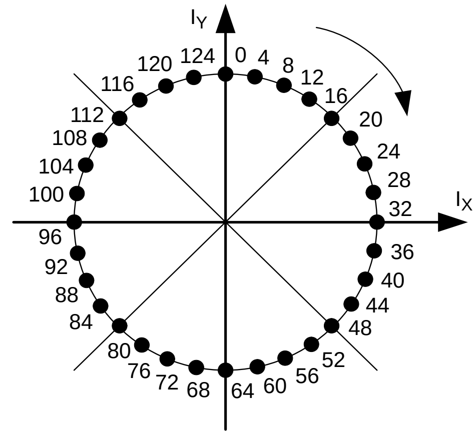

Figure 9. Possible Microstepping Positions for Correct Bemf Measurement (1/8 Microstepping)

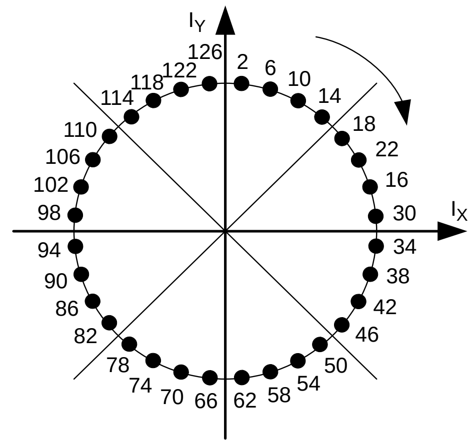

Figure 10. Example of 1/8 Microstepping with Offset

Table 1. MICROSTEP POSITIONS FOR DIFFERENT STEPPING MODES (NO OFFSET)

Stepping Mode						Stepping Mode						Stepping Mode				
1/32	1/16	1/8	1/4	1/2		1/32	1/16	1/8	1/4	1/2		1/32	1/16	1/8	1/4	1/2
0	0	0	0	0		43						86				
1						44	44	44				87				
2	2					45						88	88	88	88	
3						46	46					89				
4	4	4				47						90	90			
5						48	48	48	48	48		91				
6	6					49						92	92	92		
7						50	50					93				
8	8	8	8			51						94	94			
9						52	52	52				95				
10	10					53						96	96	96	96	96
11						54	54					97				
12	12	12				55						98	98			
13						56	56	56	56			99				
14	14					57						100	100	100		
15						58	58					101				
16	16	16	16	16		59						102	102			
17						60	60	60				103				
18	18					61						104	104	104	104	
19						62	62					105				
20	20	20				63						106	106			
21						64	64	64	64	64		107				
22	22					65						108	108	108		
23						66	66					109				
24	24	24	24			67						110	110			
25						68	68	68				111				
26	26					69						112	112	112	112	112
27						70	70					113				
28	28	28				71						114	114			
29						72	72	72	72			115				
30	30					73						116	116	116		
31						74	74					117				
32	32	32	32	32		75						118	118			
33						76	76	76				119				
34	34					77						120	120	120	120	
35						78	78					121				
36	36	36				79						122	122			
37						80	80	80	80	80		123				
38	38					81						124	124	124		
39						82	82					125				
40	40	40	40			83						126	126			
41						84	84	84				127				
42	42					85										

Transparency Mode

It's not 100% correct to say that the voltage on the SLA-pin will represent the real Bemf voltage of the stepper motor if a microstep position is located at the "coil current zero crossing". At the moment the current less state is entered, the coil voltage is measured. Because at that moment the coil current will not yet be zero (it takes time to get all the current out of the coil), the coil voltage will clamp to the power supply voltage (VBB) + 0.6 V. Once the coil current is zero, the coil voltage will decay (transient behavior). The coil voltage will decay to the Bemf voltage of the stepper motor. It's only at that moment that the coil voltage will be equal to the Bemf voltage of the motor!

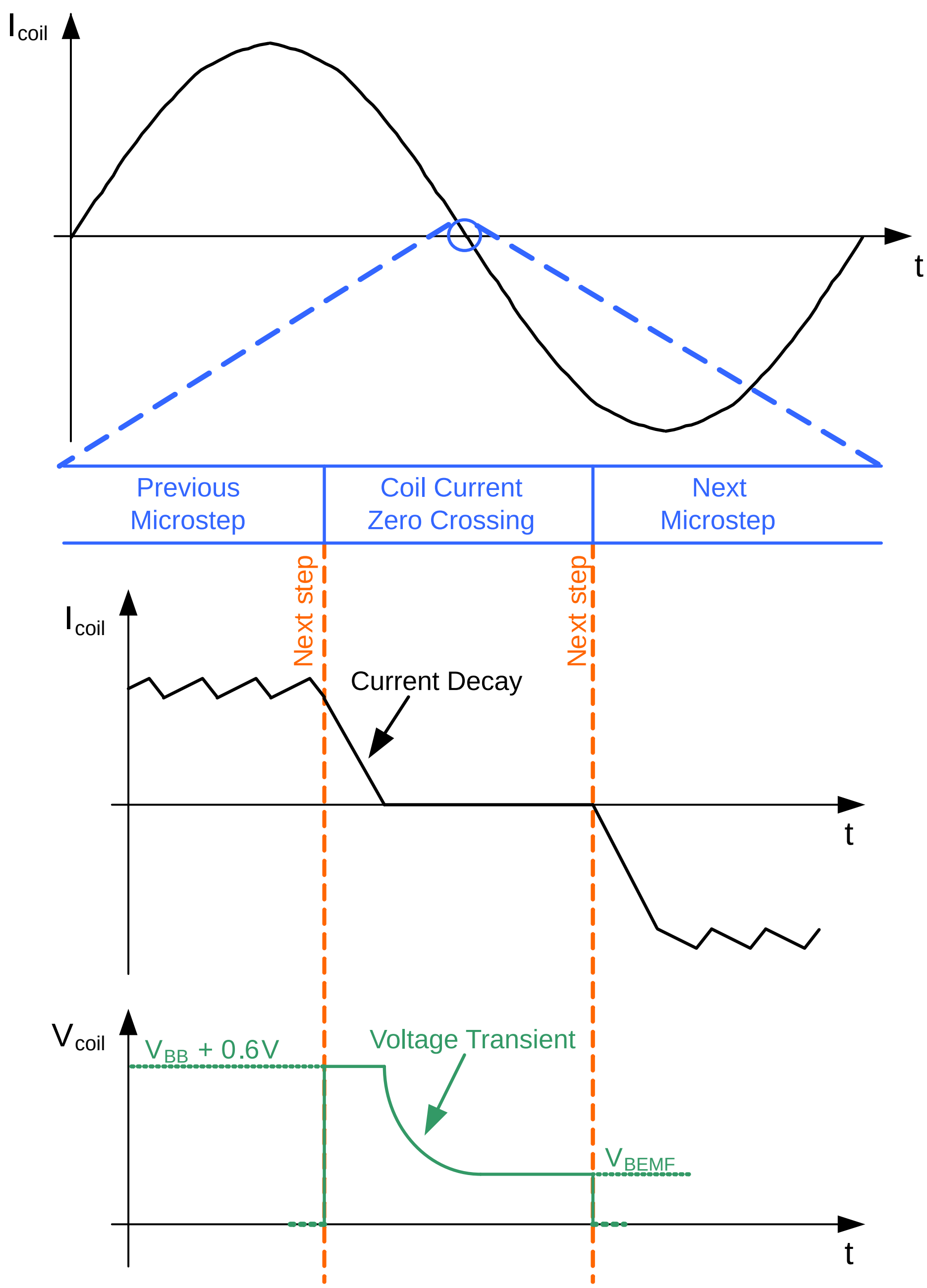

Figure 11. Coil Voltage Behavior During Current Less State

If the speed of the stepper motor is set too high, it's possible that the next (micro)step is set before the transient behavior has ended. If this is the case, the voltage on the SLA-pin will never represent the real Bemf voltage.

To help determining if this is the case, AMIS−305xx has a so called 'transparent' mode. In this mode the coil voltage during the current less state can be measured on the SLA-pin. This makes it possible to monitor the transient behavior of the coil voltage during this stage and to verify if the real Bemf voltage of the stepper motor can be sampled.

When working in ‘transparent’ mode, the SLA voltage will be updated at the rate of the PWM frequency when the motor is located in the “coil current zero crossing”. The transient behavior can be monitored.

As can be seen in Figure 12, the transient behavior has ended before the next (micro)step is set. The real Bemf voltage of the stepper motor can be measured.

Verifying the transient behavior of the coil voltage during the current less state is only done during development (for most applications). In the final application it’s not needed to sample this complete transient behavior. For this AMIS−305xx has a so called ‘not transparent’ mode.

In this mode the coil voltage is also sampled at the PWM rate when the coil current is zero but the voltage on the SLA-pin is only updated from the moment the “coil current zero crossing” state is left (see also Figure 12). The transient behavior will not be seen by the microcontroller (which is also not needed for most applications).

Keep in mind that the SLA voltage is only updated when leaving the current less state. The SLA voltage measured during the current less state will actually represent the Bemf voltage of the previous full step.

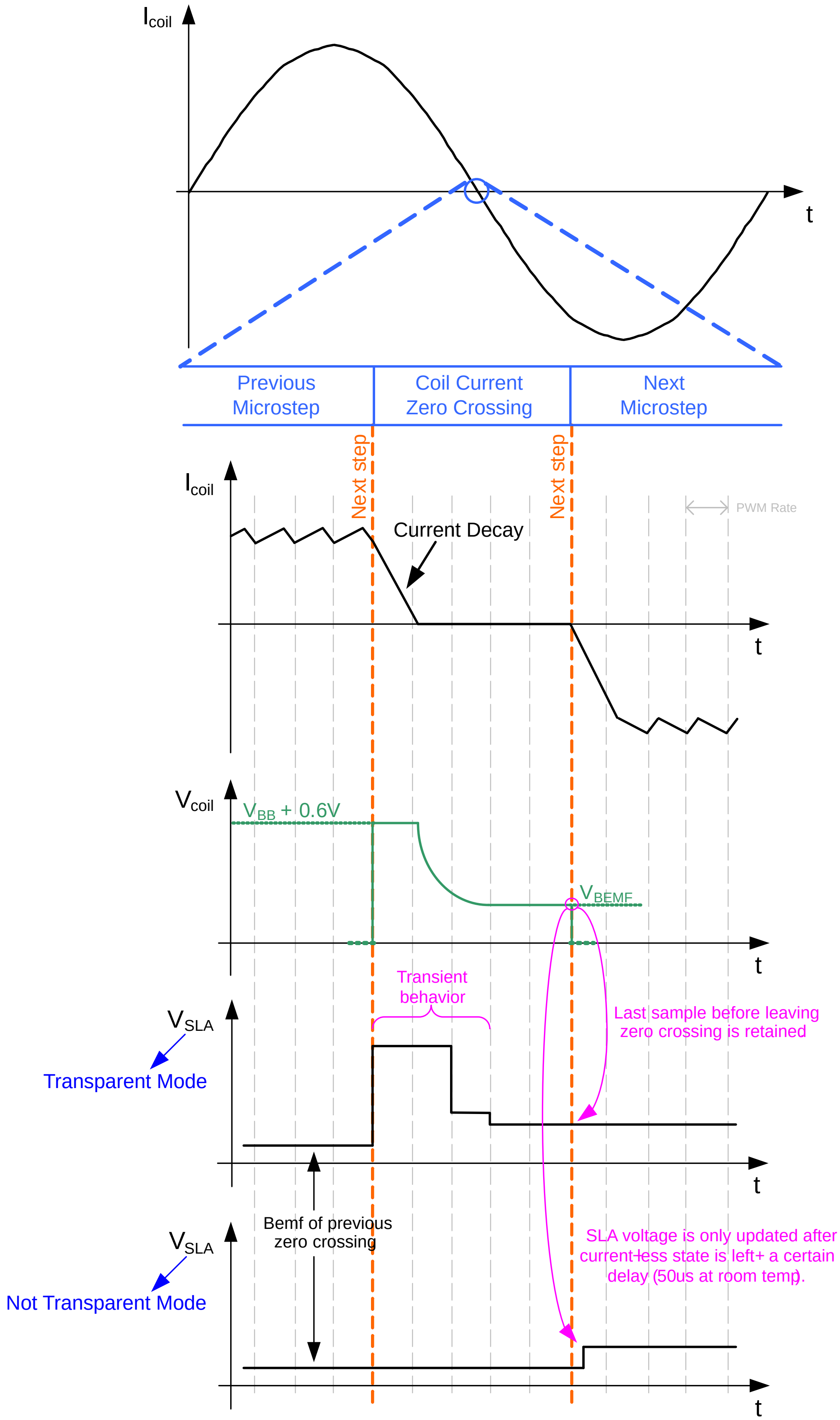

Figure 12. Voltage Measured on the Coil and SLA-pin for ‘Not Transparent’ Mode

Maximum Operating Speed

As explained in *Transparency Mode*, one needs to be careful when to measure the BEMF. After the start of the coil current zero crossing it takes some time before the real BEMF can be measured (see Figure 11). Leaving the coil current zero crossing stage too early will result in an incorrect BEMF sampling (= the measured voltage on the SLA-pin will not represent the real BEMF). This will limit the maximum operating speed.

The maximum operating speed will depend on next parameters:

- Stepper motor
- Coil current
- Operating voltage
- Stepping mode

It's best to choose a stepper motor with low series resistance (few Ohms or less). For high speed applications it will also be important to choose a stepper motor with low inductance.

The coil current has to be defined in such a way that enough torque is produced by the stepper motor to rotate the load without loosing steps.

For silent operation, a high stepping mode is advised. But as will be seen later, this will limit the maximum rotation speed.

The operating voltage will depend on the used motor, operating speed and coil current. It's important to operate the stepper motor within his operating range.

Finding the maximum operating speed can best be done by measuring. For this the AMIS−3052x Evaluation Kit can be used. This Evaluation Kit can be ordered from the ON Semiconductor website (www.onsemi.com). Below steps explain how to determine the maximum operating speed by using the AMIS−3052x EVK.

Step 1: Remove capacitor C3 from the AMIS−3052x Motherboard (schematics and layout can be found in the Graphical User Interface). This capacitor will filter the SLA signal. Although it's advised to add this capacitor in the final application, this capacitor will influence our measurement and should be removed.

Step 2: Build the Evaluation Kit setup (see documentation provided with the Evaluation Kit). Make sure that the correct operating voltage is used (connect your own power supply if needed) and that the correct stepper motor is used.

Step 3: Do not connect any signal to the NXT-pin!

Step 4: Press the CLR-pin one time to clear the digital.

Step 5: Set the Coil Current and Stepping Mode (Control Register 0).

Step 6: Set SLA Transparency to Transparent and enable the motor driver (Control Register 2).

Step 7: Connect the NXT signal. Set the NXT frequency very low. Rotor should be rotating very slowly resulting in no BEMF.

Step 8: Verify if there is no offset created by reading the Microstepping Position (Status Register 3). This can easily be done by enabling Check SLA Output in the Graphical User Interface (GUI) of the AMIS−3052x Evaluation Kit (see Figure 13). When checked, the Microstepping Position will color red if an offset is created (when Status Register 3 is read out).

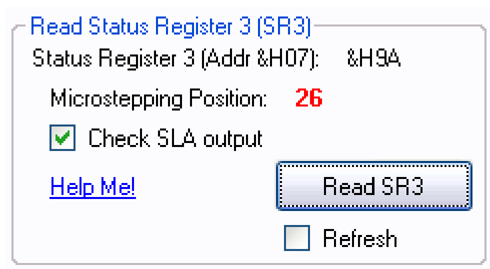

Figure 13. Check SLA Output

If the Microstepping Position colors red after reading out SR3, go back to Step 1!

Step 9: Measure the coil current in one of the coils, measure the voltage on the SLA-pin and monitor the NXT-pin. Best is to trigger the oscilloscope on the coil current zero crossing. Figure 14 gives the results measured with a Nidec Servo stepper motor operated at 12 V and 415 mA coil current. Stepping mode was set to 1/8 microstepping.

A zoom is taken on the coil current zero crossing. At the rising edge of the NXT signal (purple curve) the coil current will be regulated to zero. Notice that the SLA voltage (yellow curve) claps to 5 V. This is because the coil voltage (not visible on the oscilloscope plot) will clamp to Vbat + 0.6 V (see Figure 11). After this you see the SLA voltage drop to zero. This is the transient part (see Figure 11). Keep in mind that the SLA voltage is only update at the PWM frequency rate (this gives the steps in the SLA voltage).

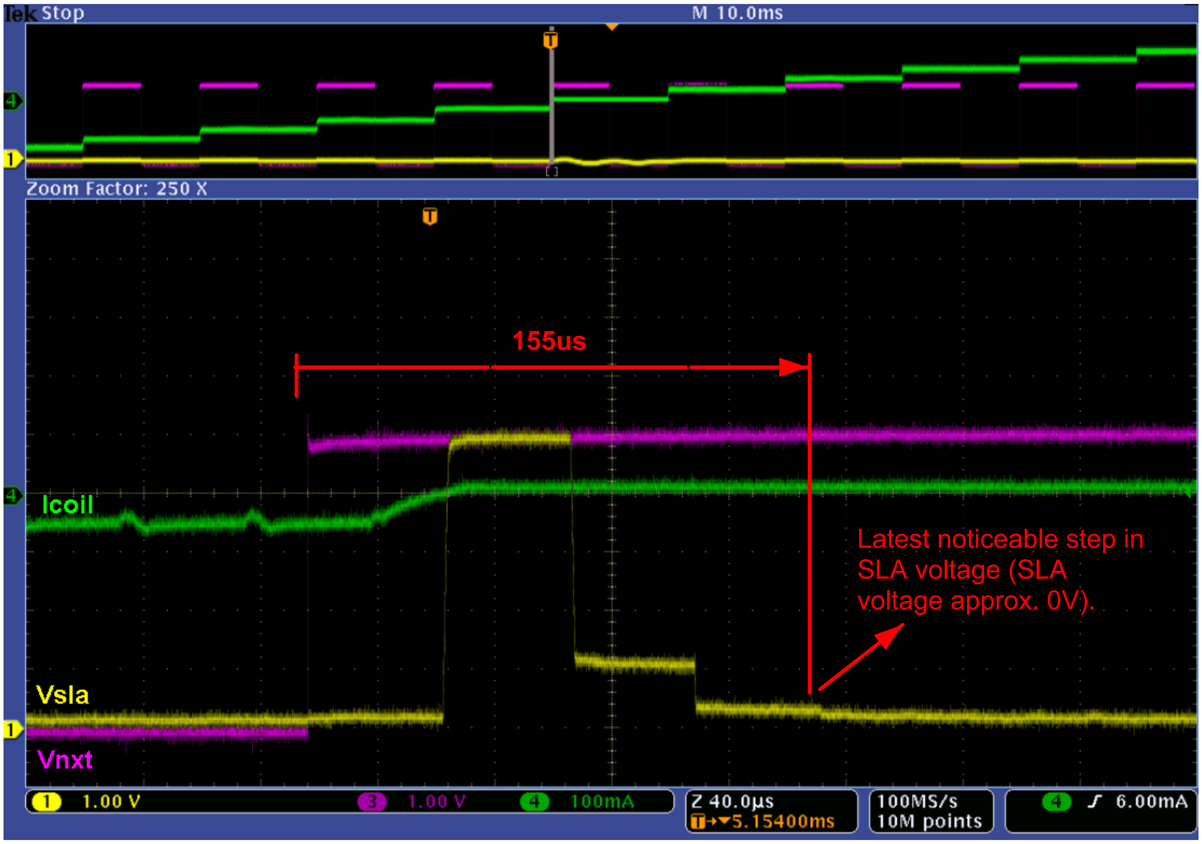

Figure 14. Define Maximum Operating Speed

The time measured between the rising edge of the NXT signal (purple curve) and the latest noticeable step in the SLA voltage (yellow curve) will define the maximum operating speed.

As can be seen in Figure 14 this time is about 155 µs.

Knowing that the stepping mode taken is 1/8 microstepping and that the coil current zero crossing should at least take 155 µs, the maximum NXT frequency is:

$$\frac{1}{155\ \mu s} = 6450\ \text{Hz} \qquad \text{(eq. 1)}$$

This will result in a velocity of:

$$\frac{6450\ \text{Hz}}{8} = 806\ \frac{\text{FS}}{\text{sec}} \qquad \text{(eq. 2)}$$

Figure 15 displays the result at 800 FS/sec (close to the maximum speed). The measured SLA voltage at this speed will still represent the real BEMF (measured at the end of the zero crossing).

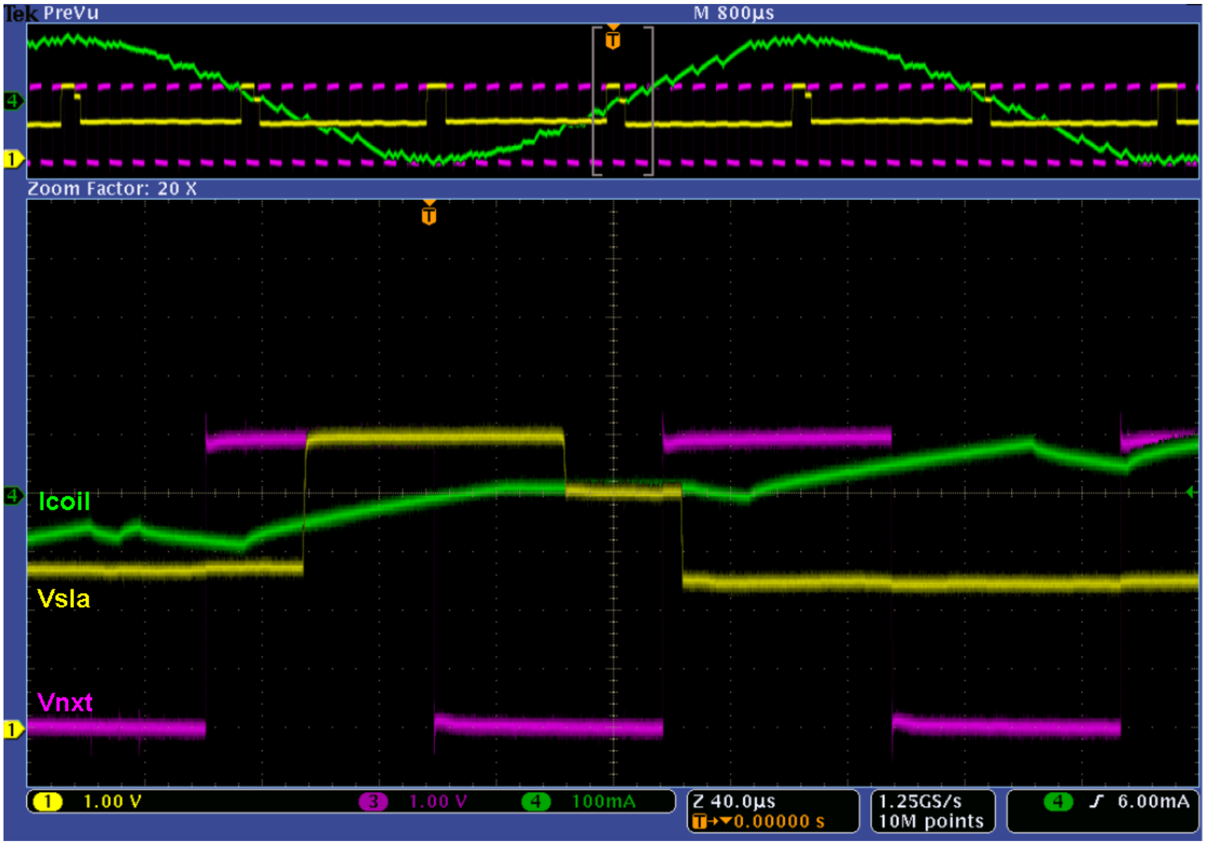

Figure 15. SLA Voltage at 800 Full Steps / sec

Notice the stable SLA-voltage in Figure 16 when the SLA Transparency is set to Not Transparent (Control Register 2). In Not Transparent the clamping and transient behavior is removed from the SLA signal giving a better view on the BEMF (see also Figure 12).

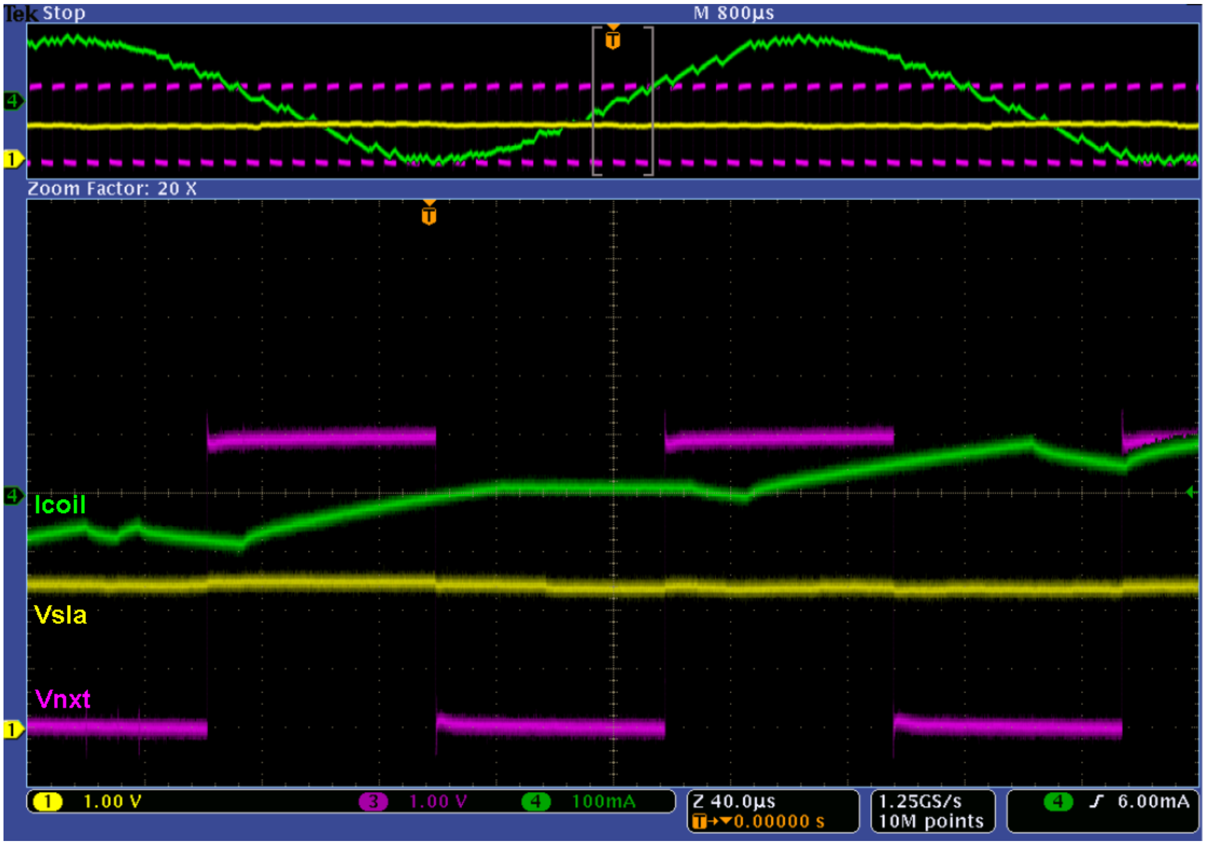

Figure 16. SLA Voltage at Maximum Speed in Not Transparent Mode

Notice in Figure 16 that the measured SLA voltage is about 2.5 V. If the measured voltage would be clamped to 5 V it's possible that the generated BEMF is too high. Set the SLA Gain to 1/4 (Control Register 2).

When the NXT frequency is increased to 7 kHz (875 FS/sec), the BEMF is sometimes sampled too fast resulting in an incorrect SLA voltage (see Figure 17). The jumps in the SLA voltage is because the coil current zero crossing is left too early and the transient part is sampled (see also Figure 11).

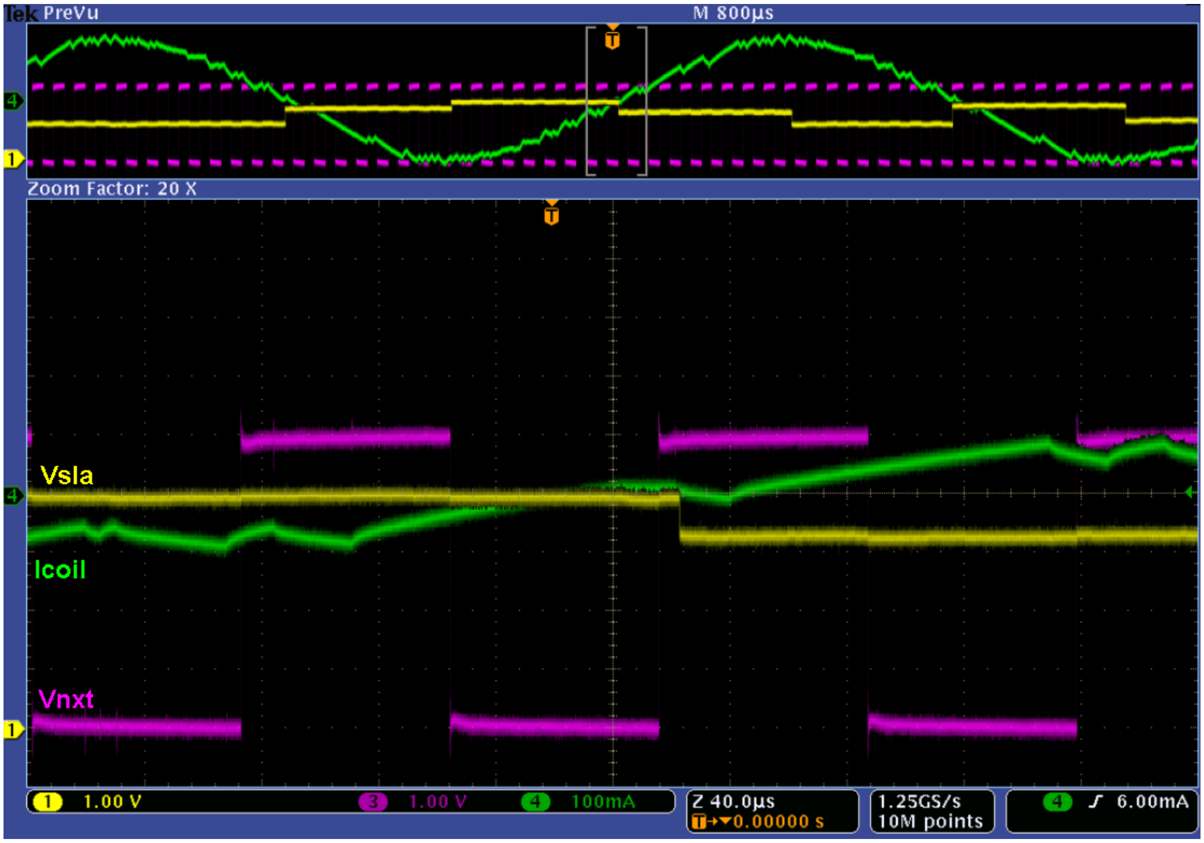

Figure 17. Too High Speed Results in Incorrect BEMF Sampling

If the maximum operating speed is lower than the required operating speed, some of the application parameters need to be changed to increase the maximum operating speed. Next are some possible adjustments that could be done.

- Choose stepper motor with lower series resistance
- Choose stepper motor with lower inductance. Keep in mind that this will have an effect on the torque!
- Increase the operating voltage
- Choose a lower coil current. Keep in mind that this will result in a lower torque.
- Choose a lower stepping mode (1/4 instead of 1/8 for instance). This will result in longer coil current zero crossings.

A trick to increase the maximum operating speed without the need of changing any of the above parameters is by stretching the coil current zero crossing. This principle is also used in AMIS−3062x (see www.onsemi.com) and is called MinSamples. See Application Note AND8371/D for more info on this.

Full Step Stepping Mode

All explanation given above is only valid if the stepping mode is not set to full step. This is because after a hard reset of the motor driver, full step mode will always start from a half step position meaning that no microstep position will be located on the “coil current zero crossing” (see also Figure 1). Creating an offset on purpose to move the step positions to a “coil current zero crossing” will not be possible making Bemf measurement in this stepping mode impossible.

There is however a possibility to operate the stepper motor in full step mode and measure the Bemf voltage. Follow next steps to operate the stepper motor in full step mode by using AMIS−305xx half step stepping mode setting.

1. Reset motor driver
2. Set coil current. Set the stepping mode to compensated half step.
3. Enable the motor driver (stepper motor should be located in a full step position)
4. Every time a full step has to be set, apply two NXT-pulses fast after each other (keeping NXT-pin limitations in mind).

In the next figure one can see that the stepper motor is running in full step mode although the stepping mode of AMIS−305xx is set to compensated half step. Because of the relative high inductance of the motor, the very short time between the two NXT-pulses (see zoomed part of Figure 18) and the internal delay of the driver, the half step position will never be reached on time. The stepper motor will run in full step mode.

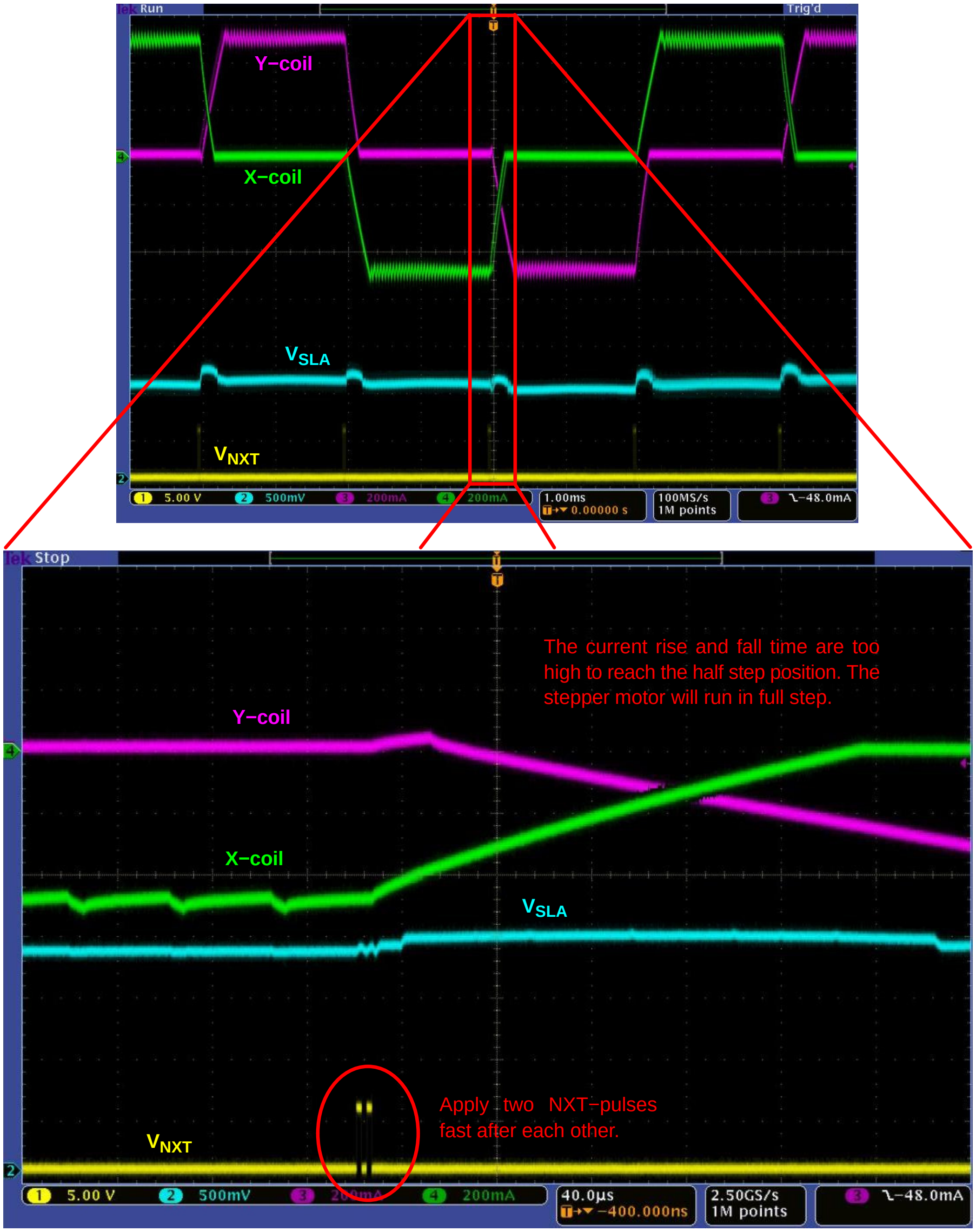

Figure 18. Operating Stepper Motor in Full Step by Using Half Step Stepping Mode

High Temperature

When operating the stepper motor driver at high temperature it is possible that the SLA voltage drops between two samples taken. This could create unwanted results. For this reason it's important to measure the SLA voltage as fast as possible after it has been updated.

Next oscilloscope plot displays the problem.

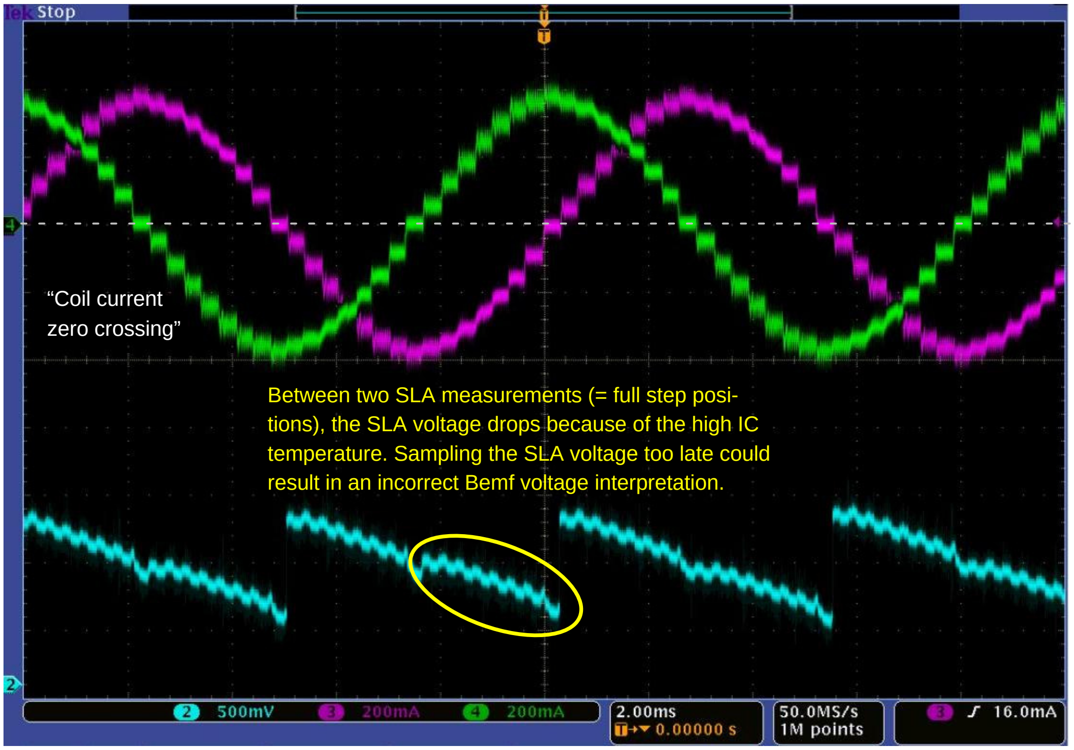

Figure 19. Decrease of SLA-voltage at High Temperature

As can be seen, the SLA voltage drops between two full step positions. If the SLA voltage is sampled too late by the microcontroller or DSP, an incorrect Bemf voltage interpretation will occur. If the SLA voltage is sampled right after it has been updated, the temperature effect will have a minimum influence on the result.

Good PCB design can reduce the drop of the SLA-voltage. If a large enough PCB heat sink is foreseen or an additional head sink is used to get the heat out of the package, the die temperature will drop and the drop in SLA-voltage will reduce.

Sample The SLA Voltage

Figure 20 gives a typical application schematic.

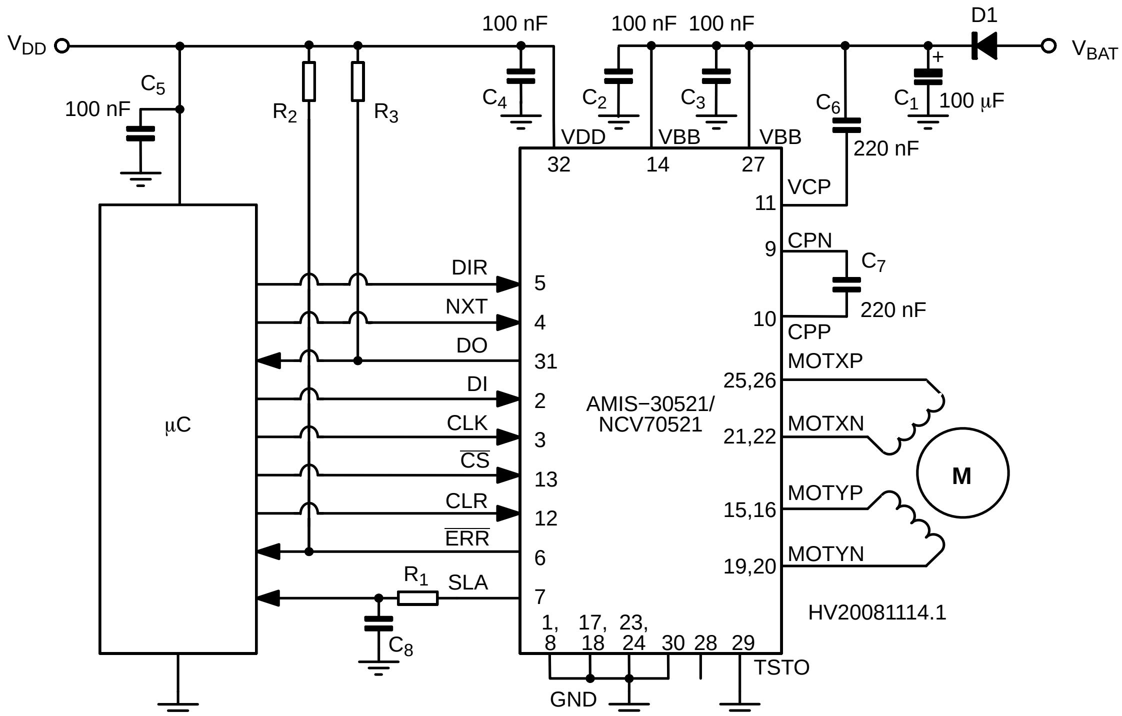

Figure 20. Typical Application Schematic

Sampling of the SLA voltage is done by the microcontroller ADC. Because the BEMF can only be sampled once per full step, it's not needed to have a high sampling rate. The ADC resolution depends on how accurate one wants to measure the SLA voltage[3].

As explained in Transparency Mode, the SLA voltage is only updated after the coil current zero crossing is left (Not Transparent Mode). Keep this in mind when sampling the SLA voltage. Also, the low-pass filter (R1 and C8) will introduce a delay in the measured signal.

Because the SLA voltage is updated at the PWM Frequency rate in Transparent Mode, one could already measure the BEMF during the coil current zero crossing. If one knows how long the clamping and transient parts lasts (defined in section Maximum operating Speed), the microcontroller can sample the SLA voltage right after this transient part. Or to make it even simpler, the microcontroller could sample the SLA voltage at the moment the next microstep is given by the microcontroller. No need to introduce an additional delay[4] as would be the case when working in Not Transparent mode (see Figure 21).

When working in Transparent mode, the transient behavior will be present on the SLA-pin. The microcontroller should just ignore this.

3. The coil voltage is sampled by a Sample-and-Hold circuit. There is no digital conversion done by AMIS−305xx.
4. If the stepper motor is operated close to the maximum operating speed it's advised to introduce a delay between the NXT pulse and sampling of the SLA voltage.

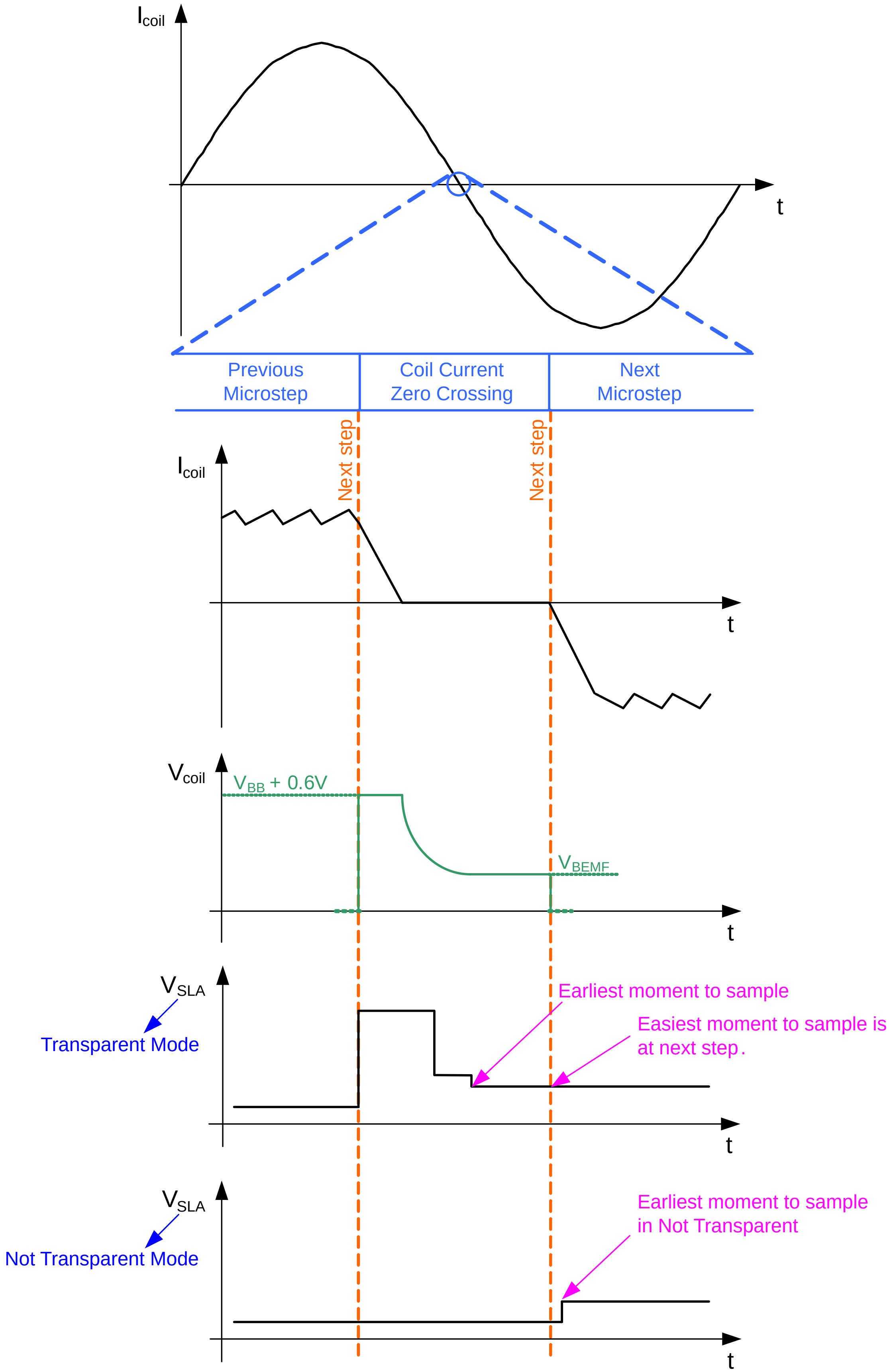

Figure 21. Difference Between Transparent and Not Transparent Mode

Examples

Below some examples are given on how to use the SLA-pin. The flowchart given in these examples represent the microcontroller firmware (see Figure 20). All examples and flowcharts given in this document are solely intended to simplify the explanation and to help you better understand how to use the SLA-pin.

Drive Motor

Figure 22 displays a simple way of driving a stepper motor. In this example the SLA-pin is not used yet. The moment the application is powered, the microcontroller will be initialized. When this is done, the coil current and stepping mode will be set. The motor driver will be enabled and NXT pulses will be send to rotate the motor. The timer will determine the time between NXT pulses and by this determine the rotation speed. In theory the stepper motor should be accelerated to the maximum speed but this is out of the scope of this document. We assume the speed is low enough to start without acceleration. The rotation speed must also be lower than the maximum operating speed (see Section Maximum operating Speed).

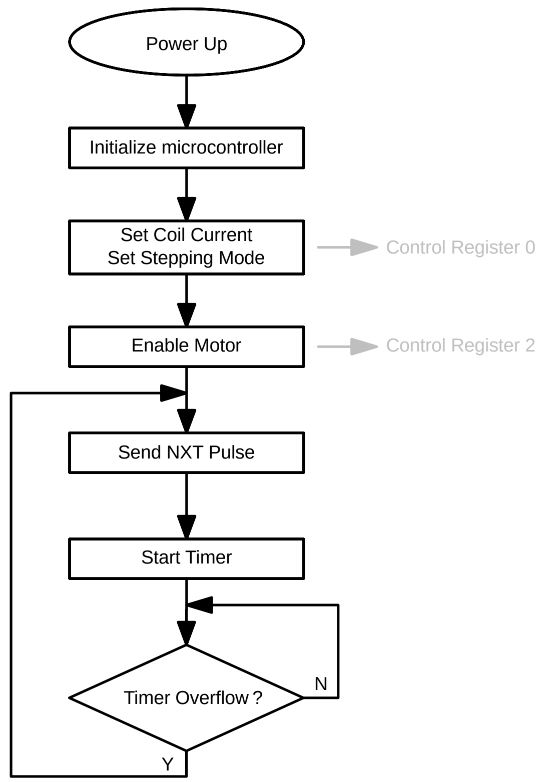

Figure 22. Simple Motor Control Example

Above flowchart is a very simple example of driving a stepper motor. No diagnostics is done, no verification if stepper motor is rotating, ... The only intention of this example is to rotate the motor with a minimum of overhead. Driving a stepper motor in real life applications will be more complex but is out of the scope of this document.

Sample SLA

The flowchart in Figure 23 gives the moment when to sample the SLA voltage when working in 1/8 microstepping.

Every time a NXT pulse is send the microcontroller will check if the coil current zero crossing phase is left. If so, the microcontroller knows the SLA voltage will be updated and will sample the SLA-pin. An additional delay is added before sampling the SLA-pin (internal update delay of motor driver, see Transparency Mode).

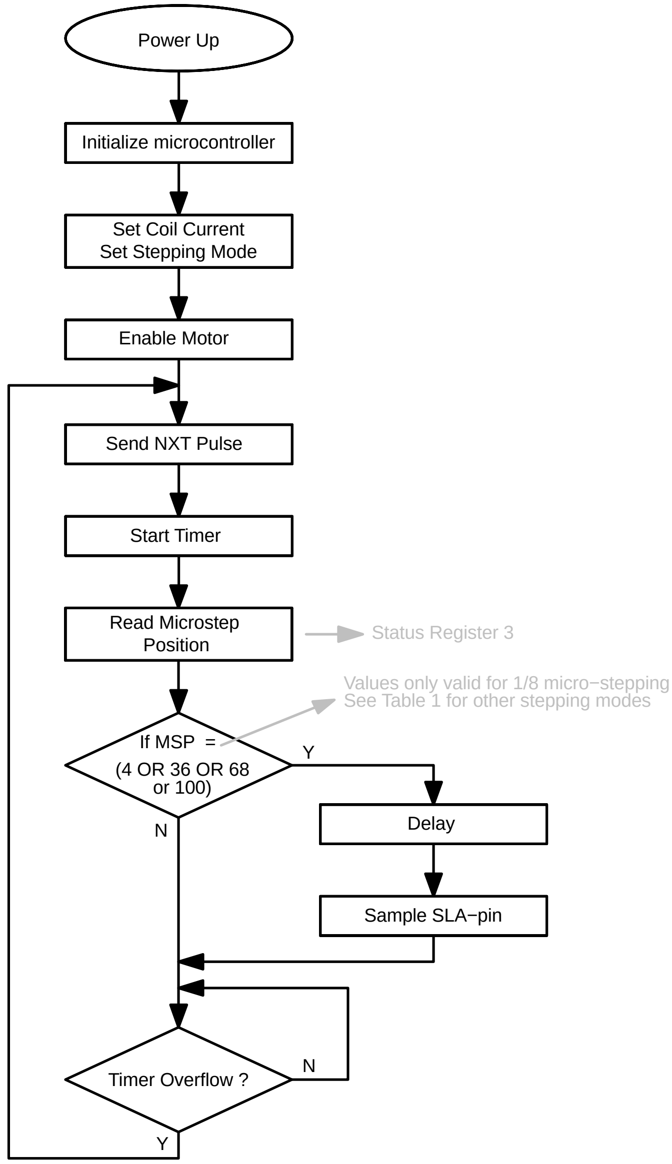

Figure 23. Sample SLA Voltage (1/8 Microstepping)

The disadvantage of above flowchart is the need to read out the Microstep Position. Because this takes time (SPI communication), this will limit the maximum operating speed. If needed the microcontroller could implement his own positioner to keep track. This would eliminate the needed SPI communication. This is however out of the scope of this document.

Above flowchart can be used when transparency mode is set to Not Transparent or Transparent. However, if Transparent is used the delay before sampling of the SLA-pin can be removed.

If Transparent mode is chosen, the SLA-pin could already be sampled during the coil current zero crossing. This is given in Figure 24.

When the coil current zero crossing is entered, the SLA-pin will be sampled. A delay is added before sampling. In this case this delay is needed to make sure the clamping and transient phase are ended and the real BEMF is sampled (see also Figures 11 and 21).

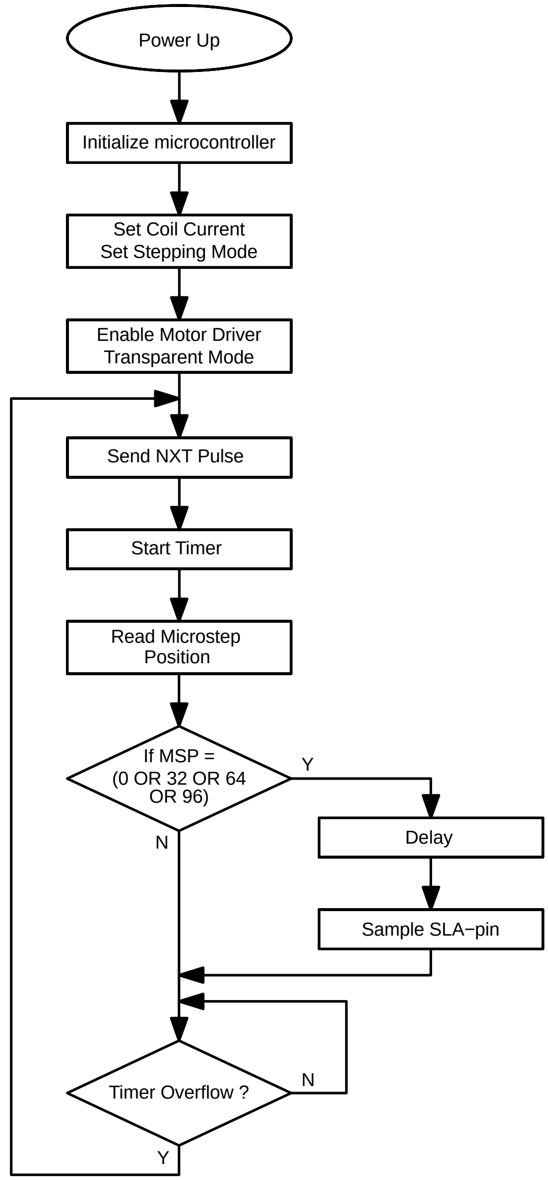

Figure 24. Sample SLA Voltage in Transparent Mode

Stall Detection

The flowchart in Figure 25 gives a simple implementation of stall detection (based on Figure 24). The sampled SLA voltage will be compared to a threshold value. If the sampled SLA voltage is below the threshold, motion will be stopped. The threshold has to be set in such a way that the sampled SLA voltage is higher than the threshold when the motor is free running. If the motor gets blocked, the BEMF will drop and by this also the SLA voltage resulting in a stall detected. Motion will be stopped.

Implementing the flowchart as given in Figure 25 will most probably fail. This because the SLA voltage is already sampled at the first coil current zero crossing. During start of the rotation oscillations will be seen in the BEMF (acceleration of the rotor) and by this also in the SLA voltage. It's possible that these oscillations trigger the stall detection although no stall is present. It's best to skip the stall detection for the first full steps. This is however out of the scope of this document.

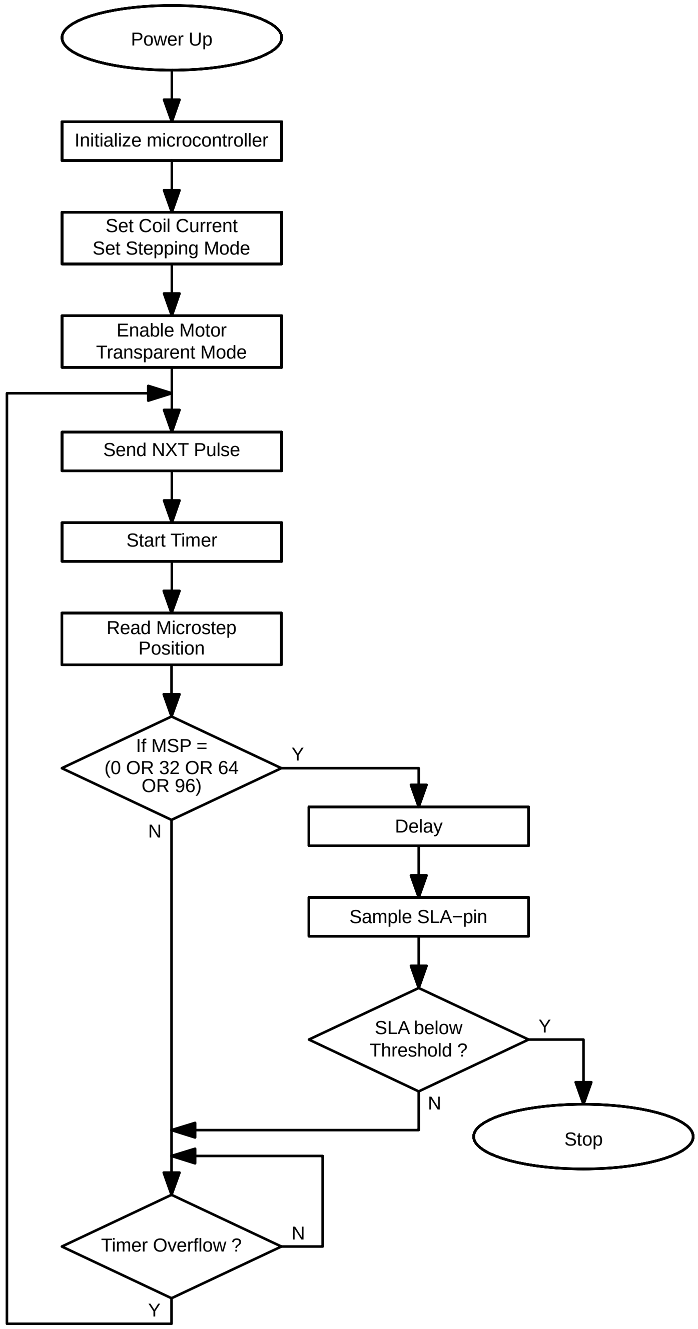

Figure 25. Simple Stall Detection

SLA Check

With the flowchart given in Figure 25 we are able to sample the SLA voltage in a correct way and to perform simple stall detection. The only issue that could occur is an offset. If for some reason an offset is created, no microstep will be located anymore on the coil current zero crossing. The SLA voltage can not be sampled nor can stall detection be done.

Figure 26 gives a simple solution to this problem. If an offset is detected, motion is stopped. In a real life application the microcontroller could do corrective actions or report the problem. This is out of the scope of this document.

MSP = Microstep Position
MOD = Remainder of a division
Y = 2 for 1/16 microstepping, 4 for 1/8 microstepping
8 for 1/4 microstepping and 16 for half stepping

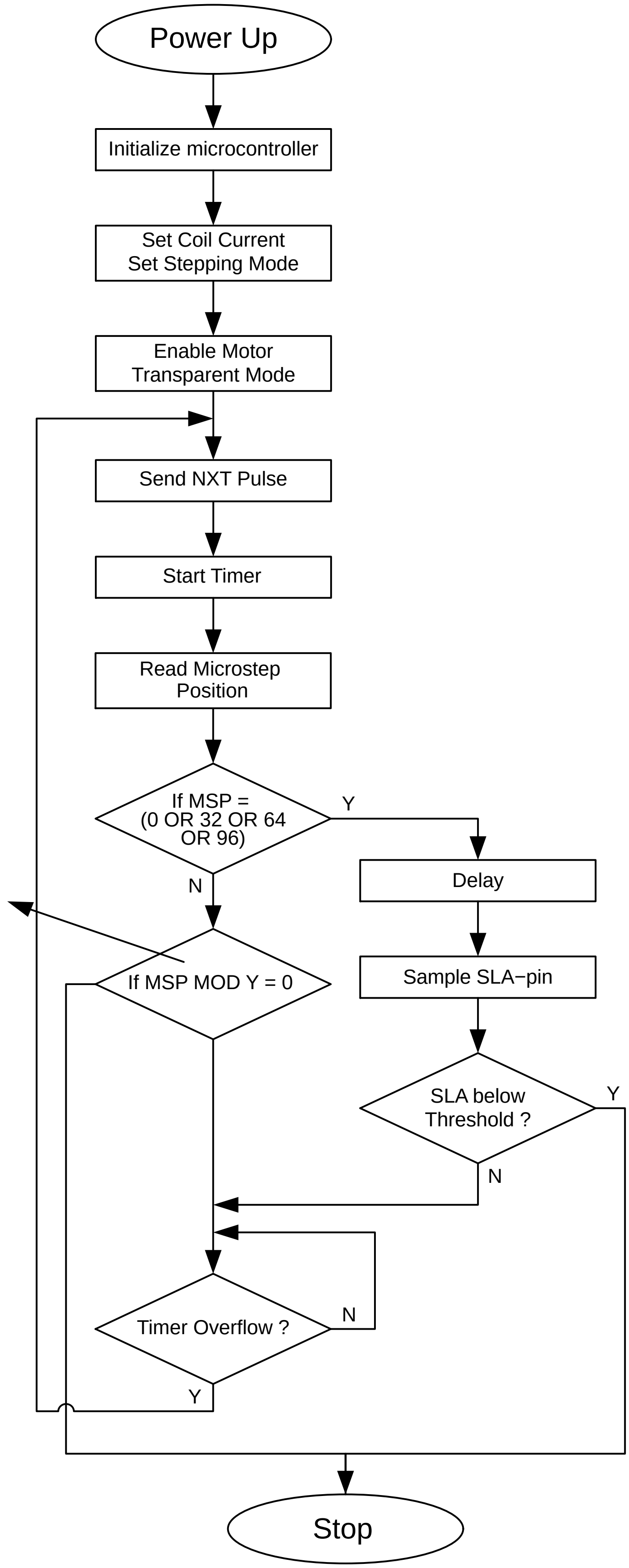

Figure 26. SLA Check

By sampling the SLA-pin as given in Figure 26, one samples the SLA-pin at the correct moment to make sure that the real BEMF is measured. An offset will be detected as well as a stall condition. By sampling the SLA-pin at the right moment, temperature effect will be eliminated (see High Temperature).

Microcontroller without ADC

To implement above flowcharts one needs to use a microcontroller with ADC. In some cases this ADC is not available. A simple way to enable stall detection in this case is by using a comparator.

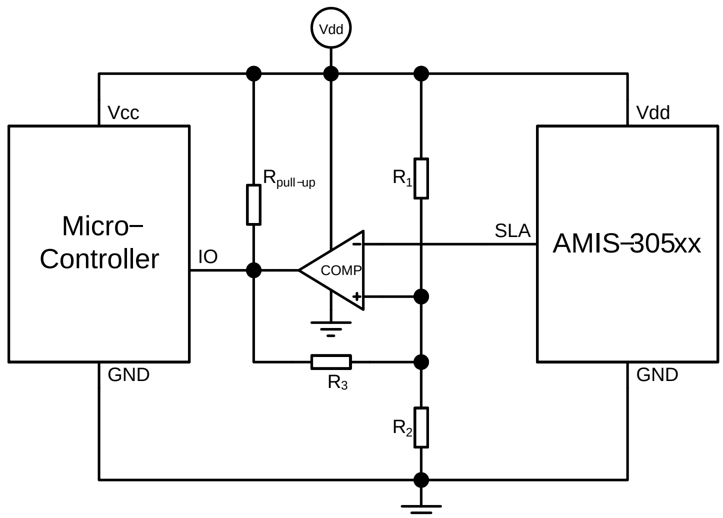

Figure 27. Stall Detection with Comparator

R1 and R2 set the threshold level. R3 adds a hysteresis to avoid toggling caused by noise. The microcontroller can check if the SLA voltage is above or below the threshold level by monitoring the digital IO pin.

The way to implement stall detection stays similar. The only difference with the flowchart in Figure 26 is that instead of sampling the SLA voltage with an ADC, the status of the IO pin is checked to determine if SLA voltage is above or below the threshold level. The moment the status of this digital IO is checked stays the same.

If a variable threshold is needed, R1 and R2 can be replaced by a potentiometer or even by a digital potentiometer controlled by the microcontroller (see www.onsemi.com for Digital Programmable Potentiometers and Comparators).

R3 is not mandatory but is advised to avoid toggling cause by noise on the SLA-pin. If R3 is not used, a low-pass filter should be added to the SLA-pin (see also Figure 20).

Working with a digital IO can also be beneficial to offload the CPU of the microcontroller. Sampling an analog value could take some time. Monitoring a digital pin gives low CPU load.

Conclusion

Implementing the best stall, steploss or torque adaptive algorithm is useless if the SLA-pin of AMIS−305xx is not used properly. By following some simple guidelines, the SLA-pin can be used in a correct and reliable way.

References

[1] AMIS−305xx Data Sheet (www.onsemi.com)

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